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13. ABSTRACT (Maximum 200 words)

The objective of this study was to understand the interaction between deep convection in the Labrador Sea and mesoscale eddies, in order to quantify the influence of convective events on the large-scale circulation. Three-dimensional non-hydrostatic numerical simulations were used to examine the response of individual eddies and groups of mesoscale eddies to surface cooling and convection. The mesoscale eddies are destabilized by the convective mixing, and break up into smaller eddies. A vigorous horizontal velocity field develops, which serves to efficiently stir the water, except for isolated eddy cores. The interleaving associated with the eddies gives rise to significant density-compensated variability in the tracer fields. The statistics of fields observed by isobaric floats are significantly affected by the eddy dynamics. Many of these features are also found in recent observations from the Labrador Sea.

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# Mesoscale Variability in the Labrador Sea

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## LONG-TERM GOALS

My long-term objective is to understand how deep convection, induced by strong buoyancy forcing at the ocean surface, influences the ocean circulation through convective plumes and geostrophic eddies.

## OBJECTIVES

My immediate objective is to understand the interactions between convection and mesoscale circulation, in order to quantify the influence of convective events on the large scale circulation. Such interactions include:

(a) The lateral mixing generated by baroclinic instability and geostrophic eddy interactions. How efficient are lateral mixing processes in convective regions? Can these processes account for the relatively homogeneous water mass found in the Labrador Sea in spring, in contrast to the highly spatially variable winter convection observed?

(b) The formation and persistence of isolated chimneys of convected fluid. Observations reveal isolated cores of dense fluid with distinct water mass properties many months after convection ceases. How do such isolated cores persist despite the homogenization hypothesized above?

(c) The tracer variability. What are the mechanisms responsible for generation of tracer variability observed on a variety of scales in the Labrador Sea? Are plumes or eddies more effective at generating variability? How is tracer variability dissipated following convection?

(d) Float signatures of mesoscale eddies in convection regions. How are isobaric float statistics influenced by the presence of a convective mesoscale eddy field? What are the float signatures of the eddies and the plumes?

## APPROACH

High-resolution numerical simulations using the Boussinesq model developed in cooperation with my colleagues Drs. Keith Julien and Joseph Werne of NCAR are carried out on grids of  $512 \times 512 \times 33$  over domains of  $50\text{km} \times 50\text{km} \times 2\text{km}$  to examine interaction between convection and single isolated eddies. To study larger domains ( $100\text{km} \times 100\text{km} \times 2\text{km}$ ) containing up to 10 geostrophic eddies in the initial conditions, an implicit gravity-wave Boussinesq model developed by Alistair Adcroft at MIT is used, enabling the use of longer timesteps. Both of these implementations of the Boussinesq equations have employed periodic side wall boundary conditions.

A float model uses the horizontal components of velocity at a specified vertical level, generated using the Boussinesq model, to advect the isobaric massless particles, and generates timeseries of velocity fields, position coordinates and tracers for each particle. Float ensemble statistics are then compared with the Eulerian statistics.

## WORK COMPLETED

(1) I have completed a series of calculations of convection in the presence of a single mesoscale eddy where the eddies are associated with compensating anomalies in Temperature and Salinity, in addition to the density anomaly as studied in our previous work (Legg, McWilliams and Gao, 1998). As the flow evolves in response to surface buoyancy loss, considerable structure on a variety of scales is generated in the temperature and salinity fields. This variability often has no signal in the density field, and is therefore "density-compensated". I have examined the budget for density compensated variability, and developed a parcel-exchange scaling argument to predict the magnitude of such variability. These results are described in an article "Temperature and Salinity variability in heterogeneous convection" Legg and McWilliams, submitted to Journal of Physical Oceanography.

(2) I have carried out a series of calculations over larger area domains (100km x 100km) containing ensembles of several dense and light core eddies, and comparison calculations without any eddies. In some calculations, convective buoyancy loss is applied to the upper surface; in others no forcing is applied and in some buoyancy loss is of only limited duration. These calculations have revealed a rich interaction between the convection and geostrophic eddy dynamics. I have focused on the modification of eddy statistics (the destruction and/or merger of eddies) and the energetics by the convective buoyancy loss. The results of this study are described in an article "Convective modifications of a geostrophic eddy field", Legg and McWilliams, submitted to Journal of Physical Oceanography.

(3) Using solutions generated in the study of the interaction between convection and many geostrophic eddies, I have examined the response of isobaric drifters to the plume and eddy scale motion, both at the surface and at depths of 1000m, employing 1600 drifters for good statistics. I have compared the statistics of the drifter measured fields (vertical velocity, temperature and salinity and horizontal velocities) to the Eulerian statistics. An article describing the eddy signatures of isobaric floats is currently in progress.

(4) In collaboration with an undergraduate student, Nicholas Switanek, I have carried out a series of calculations of horizontally homogeneous convection in a small area domain (4kmx4kmx2km), to examine in detail the finite temperature and salinity gradients generated in the convective layer when both salinity and temperature gradients are present in the initial stratification. These results were presented at the American Meteorological Society Boundary Layers and Turbulence symposium in Dallas, January 1999, and a paper is currently in progress.

## RESULTS

(1) Temperature and salinity fine-structure. When both ambient stratification and a dense core eddy are associated with both salinity and temperature stratification, significant variability can be generated in the temperature and salinity fields without any corresponding density variability. This density-compensated variability can be generated through either vertical mixing or baroclinic eddy processes. I have developed a simple parcel exchange theory to predict the magnitude of density-compensated variability (figure 1). The mechanisms by which variability is created in vertical mixing regions and baroclinic eddy dominated regions differs. In vertical mixing regions parcels of water from the surface are exchanged, via convection plumes, with parcels of the same density from the stable stratification at the base of the convective layer base. In the baroclinic eddy region the interleaving exchanges parcels along isopycnals between the center of the eddy near the

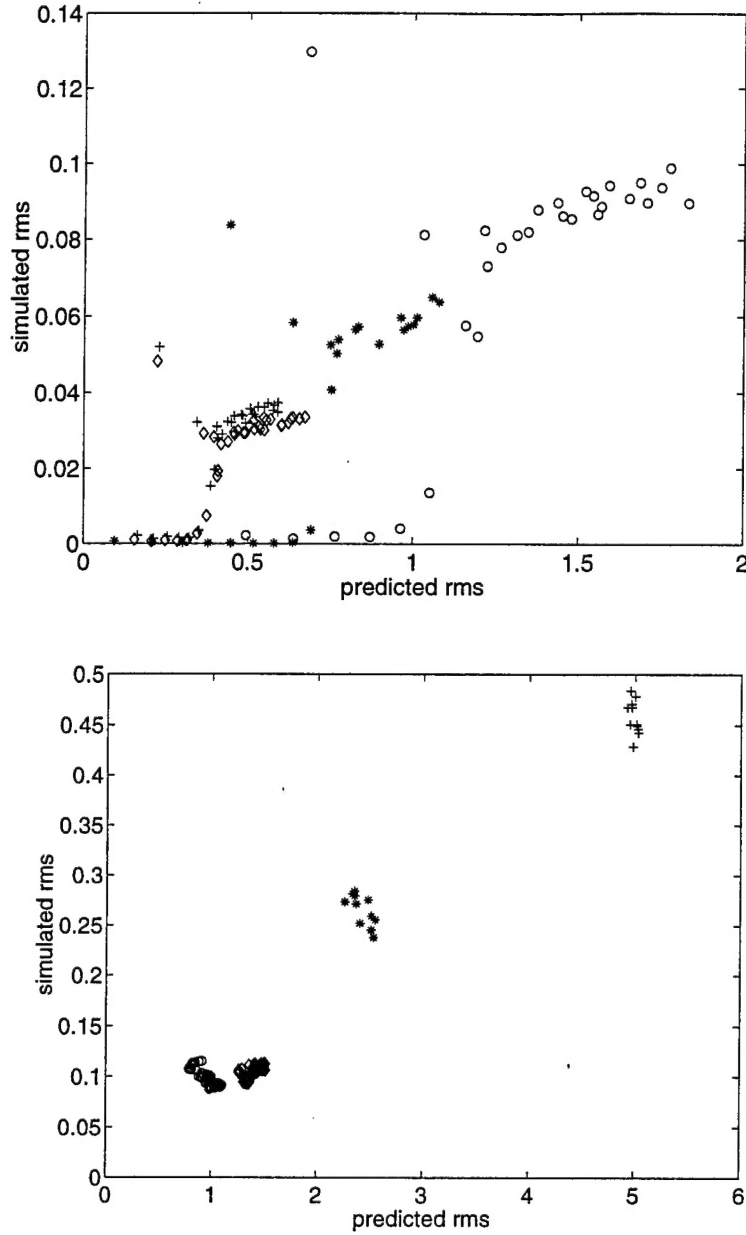


Figure 1: The simulated variance in the variable  $\tau = \beta S + \alpha T$ , shown plotted against a prediction which assumes exchange of parcels of identical density  $\rho = \rho_0(\beta S - \alpha T)$ , for (a) plume dominated regions, (b) eddy dominated regions. Different symbols represent different calculations (with different temperature and salinity stratification, and forcing). An approximately linear relationship is found between simulated and predicted values. The parcel exchange prediction gives  $\tau_{rms} = |2(1 - \gamma)(S_{1,i} - S_{2,i}) + 2\gamma(T_{1,i} - T_{2,i})|$ , where  $S_{1,i}, S_{2,i}$  are the initial salinity values at the surface and the interior location to which mixing extends, and  $T_{1,i}, T_{2,i}$  are the temperature values at those locations.  $\gamma$  is the fraction of surface buoyancy loss due to surface salinity increase (by evaporation or brine rejection).

surface, and outside the eddy below the surface. Comparison between the parcel exchange model predictions and simulated variability shows that variability is dissipated more rapidly in vertical mixing regions, and hence eddy interleaving regions are more effective at generating variability.

(2) Convective modifications of geostrophic eddy field. As for a single isolated dense core eddy, the application of surface buoyancy forcing can destabilize a baroclinic eddy, through erosion of the surface stratification, and cause it to break up via baroclinic instability. When cooling ceases the remaining eddy fragments rapidly coalesce such that a few isolated eddy cores with distinct water mass properties can persist. The fluid outside the eddy cores is however much more efficiently mixed (horizontally as well as vertically) than in the absence of convective forcing. This efficient mixing (or homogenization) is a result of a very energetic barotropic horizontal velocity field which develops when convective forcing is applied. We show that without any eddies in the initial conditions, no barotropic velocity field is generated. Convective mixing causes a direct input of kinetic energy on relatively small scales - those of convective plumes. However, at these scales, where flow is strongly 3-dimensional, the kinetic energy is rapidly dissipated. When eddies are present, convective forcing acts as a catalyst for the release of available potential energy from the eddies, via baroclinic instability. This kinetic energy input is at the larger scales dominated by geostrophic dynamics, and hence cascades to larger scales, instead of being dissipated.

(3) Behavior of floats in convecting flows. My investigations of isobaric floats in the presence of convection localized by mesoscale eddies reveal a tendency for floats to congregate in the convergent regions associated with downwelling fronts. These fronts are associated with cooler than average fluid - hence the ensemble mean temperature measured by the floats diverges from the Eulerian mean, an important consideration when interpreting observations made by such isobaric floats. As a result the net heat flux deduced from the floats is about half that found from the Eulerian measurements. In flows with considerable eddy structure, the dispersion of floats can also reveal the process of lateral exchange and restratification.

(4) Temperature and Salinity gradients in convective layers. When both temperature and salinity gradients exist in the initial stratification, convection vertically mixes density, but finite density-compensating gradients of temperature and salinity remain. Both the salinity and temperature gradient are linearly related to the initial salinity gradient when the convection is forced by cooling alone.

## IMPACTS

My research on convective dynamics should improve understanding of both the observed features of convection, and the net effects of these small-scale features on water mass transformation. This understanding provides a firmer basis for improved parameterizations of convection and predictions of sub-polar circulations and tracer distributions and the global thermohaline circulation.

## TRANSITIONS

These results are being shared with members of the ONR Labrador Deep Convection ARI. These results are included in the article documenting the Labrador Sea convection experiment (Labsea group, 1998). Recent results are being used to interpret the results of mooring measurements (Lilly et al, 1998), especially the appearance of strong barotropic eddy velocities during convection periods, and CTD measurements (Pickart et al, 1998) especially the structure in temperature

and salinity fields. Float studies are being compared with the PALACE floats of Davis, Lavender and Owens.

## RELATED PROJECTS

This work is carried out in collaboration with the "Deep convection in the Ocean" project, McWilliams PI, UCLA.

### ONR Deep Convection ARI

These simulations of convection localized by one or more mesoscale eddies provide scenarios for comparison with observations, both of the small scale velocity and temperature fields, and remote sensing signatures of the chimney scale circulation and baroclinic instability eddies. These simulations encourage the evaluation of the pre-convection eddy field for comparison with the later localized convection regions.

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